中国科学院大学
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Study of B_c mesons at LHCb

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(on behalf of the LHCb collaboration)

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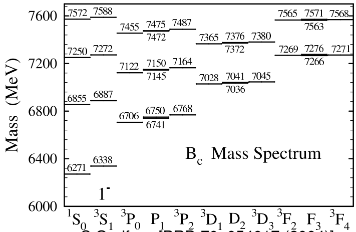
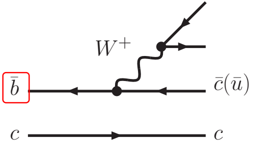
ICHEP 2018 @ Seoul, July 2018

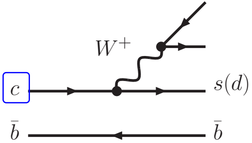
B_c physics

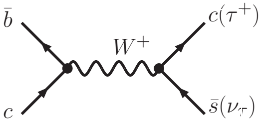


S.Godfrey, [PRD 70, 054017 (2004)]

- B_c, mesons formed by two different heavy flavor quarks, unique in the SM
- B_c^+ discovered by CDF at Tevatron
  - $B_c^+ \to J/\psi \ell^+ \nu_\ell$ [PRL 81 (1998) 2432], $J/\psi \pi^+$
- $\sigma(B_c^+)_{\mathrm{LHC}}/\sigma(B_c^+)_{\mathrm{Tevatron}} \sim \mathcal{O}(10)$, to study B_c family systematically
  - $N(B_c^+ \to J/\psi \pi^+)/\mathrm{fb}^{-1}$: $\sim$1000 at LHCb vs. $\sim$50 at CDF
- B_c^+ decay modes
  - $\bar{b} \to \bar{c} W^+$ ($\sim$20%), e.g., $J/\psi (3)\pi$, $J/\psi D_s^+$, $J/\psi \ell^+ \nu_\ell$
  - $c \to s W^+$ ($\sim$70%), e.g., $B_s^0 \pi^+$, $B_s^0 \ell^+ \nu_\ell$
  - $c\bar{b} \to W^+$ ($\sim$10%), e.g., $\bar{K}^{*0} K^+$, ϕK^+, $\tau^+ \nu_\tau$



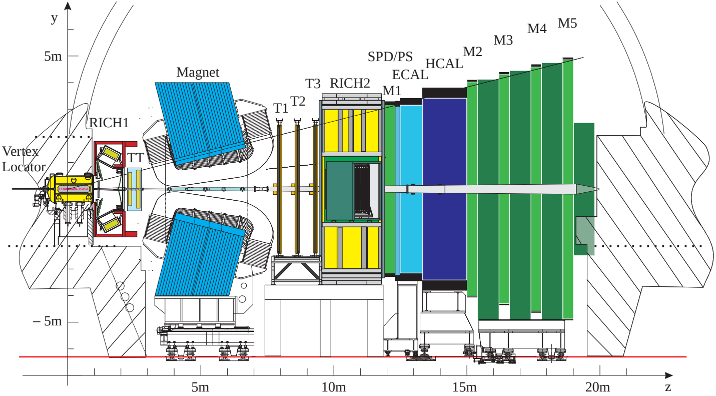




The LHCb detector and data-taking

[JINST 3 (2008) S08005]

- Acceptance $2<\eta<5$, with excellent vertexing, tracking, PID



Run-I ($3\,\text{fb}^{-1}$)
2012: $2\,\text{fb}^{-1}$ @$\sqrt{s}=8$ TeV
2011: $1\,\text{fb}^{-1}$ @$\sqrt{s}=7$ TeV

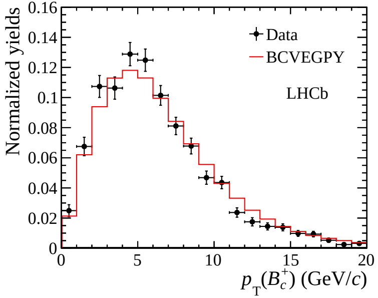
Run-II @$\sqrt{s}=13$ TeV
2017: $1.7\,\text{fb}^{-1}$
2016: $1.7\,\text{fb}^{-1}$
2015: $0.3\,\text{fb}^{-1}$

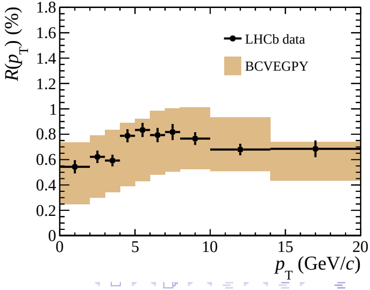
B_c studies based on LHCb Run-I data

Production	$\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\,\pi^+)/[\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi\,K^+)]$	[PRL 109 (2012) 232001] [PRL 114 (2015) 132001]
	$\sigma(B_c^+)/\sigma(B_s^0)\cdot\mathcal{B}(B_c^+\to B_s^0\pi^+)$	[PRL 111 (2013) 181801]
	$\sigma(B_c^+)/\sigma(B^+)\cdot\mathcal{B}(B_c^+\to D^0K^+)$	[PRL 118 (2017) 111803]
Mass & Spectroscopy	$M_{B_c^+\to J/\psi\,\pi^+}$	[PRL 109 (2012) 232001]
	$M_{B_c^+\to J/\psi\,D_s^+}$	[PRD 87 (2013) 112012]
	$M_{B_c^+\to J/\psi\,p\bar{p}\pi^+}$	[PRL 113 (2014) 152003]
	$M_{B_c^+\to J/\psi\,D^0K^+}$	[PRD 95 (2017) 032005]
	$B_c^{(*)+}(2S)\to B_c^+\pi^+\pi^-$	[JHEP 01 (2018) 138]
Lifetime	$\tau_{B_c^+\to J/\psi\,\mu^+\nu_\mu X}$	[EPJC 74 (2014) 2839]
	$\tau_{B_c^+\to J/\psi\,\pi^+}$	[PLB 742 (2015) 39]
Decay	$B_c^+\to J/\psi\,3\pi$	[PRL 108 (2012) 251802]
	$B_c^+\to J/\psi\,K^+$	[JHEP 09 (2013) 075] [JHEP 09 (2016) 153]
	$B_c^+\to\psi(2S)\pi^+$	[PRD 87 (2013) 071103(R)] [PRD 92 (2015) 072007]
	$B_c^+\to J/\psi\,D_s^{(*)+}$	[PRD 87 (2013) 112012]
	$B_c^+\to J/\psi\,K^+K^-\pi^+$	[JHEP 1311 (2013) 094]
	$B_c^+\to J/\psi\,3\pi^+2\pi^-$	[JHEP 1405 (2014) 148]
	$B_c^+\to J/\psi\,p\bar{p}\pi^+$	[PRL 113 (2014) 152003]
	$\mathcal{B}(B_c^+\to J/\psi\,\pi^+)/\mathcal{B}(B_c^+\to J/\psi\,\mu^+\nu_\mu)$	[PRD 90 (2014) 032009]
	$B_c^+\to J/\psi\,D^{(*)}K^{*0}$	[PRD 95 (2017) 032005]
	$\mathcal{B}(B_c^+\to J/\psi\,\tau^+\nu_\tau)/\mathcal{B}(B_c^+\to J/\psi\,\mu^+\nu_\mu)$	[PRL 120 (2018) 121801] See O. Leroy's talk [link]
	$B_c^+\to D_{(s)}^{(*)+}\overline{D}^{(*)0}, D_{(s)}^{(*)+}D^{(*)0}$ (upper limit)	[NPB 930 (2018) 563]
	$B_c^+\to B_s^0\pi^+$	[PRL 111 (2013) 181801]
	$B_c^+\to p\bar{p}\pi^+$ (upper limit)	[PLB 759 (2016) 313]
	$B_c^+\to K^+K^-\pi^+$ (upper limit)	[PRD 94 (2016) 091102(R)]
	$B_c^+\to D^0K^+$	[PRL 118 (2017) 111803]

B_c^+ production, with $B_c^+ \to J/\psi\,\pi^+$

- With 2011 (7 TeV) data [PRL 109 (2012) 232001][PRL 114 (2015) 132001]
  $\mathcal{R} = \frac{\sigma(B_c^+)\times\mathcal{B}(B_c^+\to J/\psi\,\pi^+)}{\sigma(B^+)\times\mathcal{B}(B^+\to J/\psi\,K^+)} = (0.68\pm0.10\pm0.03\pm0.05(\tau_{B_c^+}))\%$, for $p_{\mathrm{T}}(B) > 4$ GeV/c and $2.5 < \eta(B) < 4.5$
- With 2012 (8 TeV) data, $\mathcal{R}$ measured as function of (p_{T}, y), for $p_{\mathrm{T}}(B) < 20$ GeV/c and $2 < y(B) < 4.5$
  - $p_{\mathrm{T}}(B_c^+)$ well described by BcVegPy (complete α_s^4 calculation)
    [C.-H. Chang *et al.*, Comput. Phys. Commun. 174 (2006) 241]
  - Integrated $\mathcal{R} = (0.683\pm0.018\pm0.009)\%$ (3% relative precision)

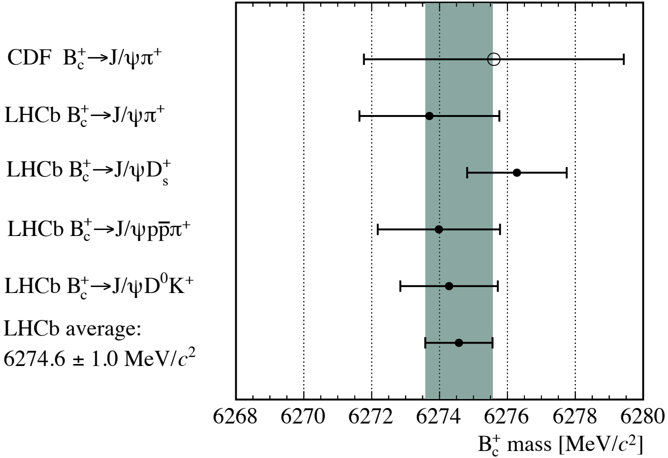




B_c^+ mass

[PRL 109 (2012) 232001][PRD 87 (2013) 112012][PRL 113 (2014) 152003][PRD 95 (2017) 032005]

- Most precise measurement! LHCb average: 6274.6 ± 1.0 MeV
  c.f. LQCD: $M(B_c^+) = 6278(4)(8)$ MeV [HPQCD, PRD 86 (2012) 094510]



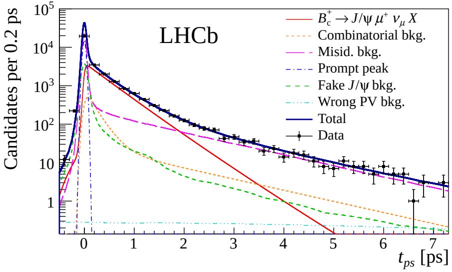
B_c^+ lifetime

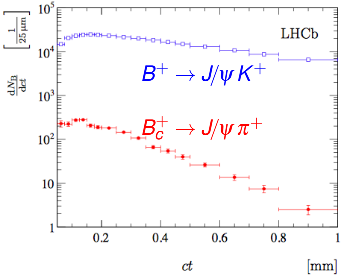
- With $B_c^+ \to J/\psi \mu^+ \nu_\mu X$, 2012 data [EPJC 74 (2014) 2839] [PLB 742 (2015) 39]
  - Lifetime unbiased selection
  - Partially reconstructed, pseudo decay time $t^* = M_{J/\psi\mu^+} \frac{L}{P_{J/\psi\mu^+}}$, K-factor from simulation used to correct for missing energy

$\tau(B_c^+) = 509 \pm 8 \pm 12$ fs

- With $B_c^+ \to J/\psi \pi^+$, all Run-I data
  - Lifetime biased selection, took ratio to $B^+ \to J/\psi K^+$
  - Decay time acceptance ratio from simulation

$\tau(B_c^+) = 513 \pm 11 \pm 6$ fs

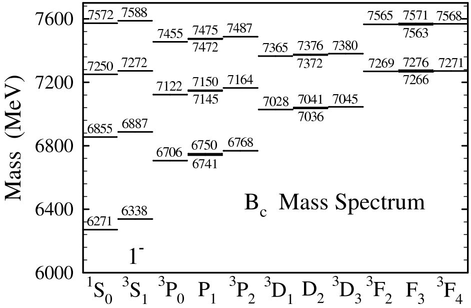




B_c excited states, decays

- Excited states, predicted branching fractions (in %)

State	Decay	GKLRY *	Godfrey †
1^3S_1	$1^1S_0+\gamma$	100	100
1^3P_2	$1^3S_1+\gamma$	100	100
$1P_1'$	$1^3S_1+\gamma$	6	12.1
	$1^1S_0+\gamma$	94	87.9
$1P_1$	$1^3S_1+\gamma$	87	82.2
	$1^1S_0+\gamma$	13	17.8
1^3P_0	$1^3S_1+\gamma$	100	100
2^1S_0	$1^1S_0+\pi\pi$	74	88.1
	$1P_1'+\gamma$		9.4
	$1P_1+\gamma$		2.0
	$1^3S_1+\gamma$		0.5
2^3S_1	$1^3S_1+\pi\pi$	58	79.6
	$1^3P_2+\gamma$		8.0
	$1P_1'+\gamma$		1.0
	$1P_1+\gamma$		6.6
	$1^3P_0+\gamma$		4.0
	$2^1S_0+\gamma$		0.01
	$1^1S_0+\gamma$		0.8



*[I. P. Gouz, *et al.*, Phys. Atom. Nucl. 67 (2004) 1559]

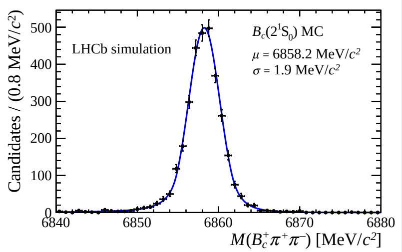
†[S.Godfrey, PRD 70 (2004) 054017]

B_c excited states, MC studies

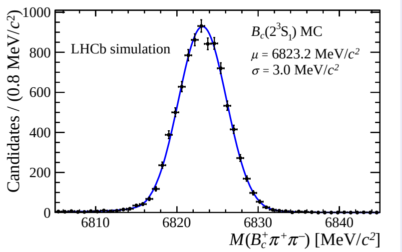
[JHEP 01 (2018) 138]

- B_c excited states, $B_c(2^3S_1)^+ \to B_c^{*+}(B_c^+\gamma)\pi^+\pi^-$, mass shifted down by $\Delta M(1^3S_1 - 1^1S_0)$ (input 67 MeV) when missing the soft photon, slightly degraded mass resolution, peak not washed out
- Possible to distinguish $B_c(2^1S_0)^+$ (input 6858 MeV), and $B_c(2^3S_1)^+$ (input: 6890 MeV) if $\Delta M(1^3S_1 - 1^1S_0) \neq \Delta M(2^3S_1 - 2^1S_0)$

$B_c^+(2^1S_0)$, $\sigma \sim 1.9$ MeV



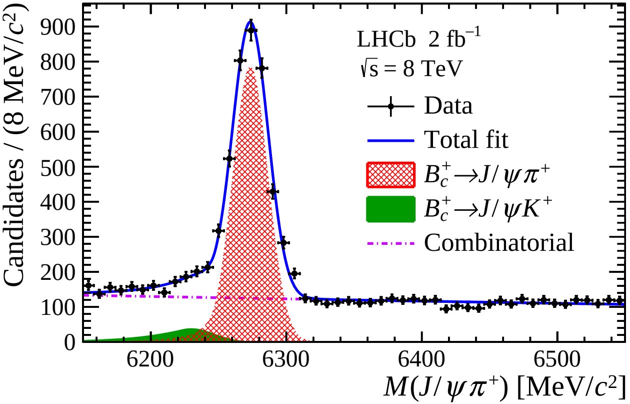
$B_c^+(2^3S_1)$, $\sigma \sim 3.0$ MeV



B_c excited states, event selection

[JHEP 01 (2018) 138]

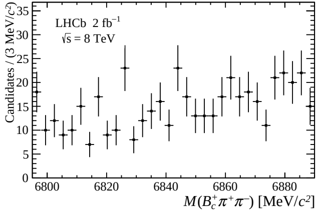
- $B_c^+ \to J/\psi\,\pi^+$, MVA-based selection, 3325 ± 73 signal
- $B_c^{(*)}(2S)^+$, B_c^+ combined with $\pi^+\pi^-$, also trained a MVA



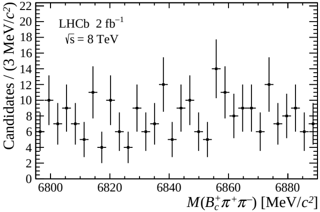
B_c excited states, mass distribution

[JHEP 01 (2018) 138]

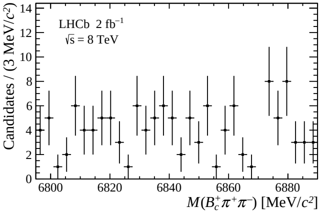
- MLP (neural network) bin with the worst S/B removed. Invariant mass distribution in other MLP bins, no sign of obvious signal



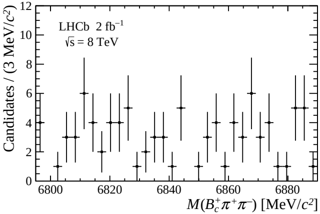
(a) MLP category: (0.02,0.2)



(b) MLP category: [0.2,0.4)



(c) MLP category: [0.4,0.6)

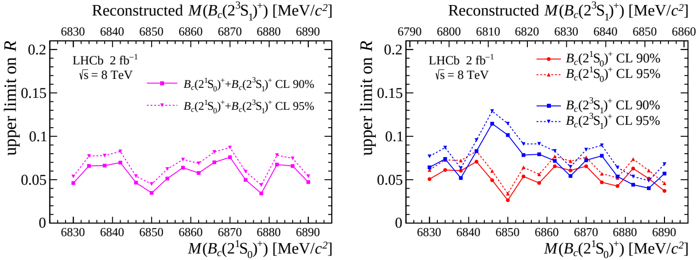


(d) MLP category: [0.6,1.0]

B_c excited states, results

[JHEP 01 (2018) 138]

- Setting upper limit on $\mathcal{R} = \frac{\sigma(B_c^{(*)}(2S)^+)}{\sigma(B_c^+(1S))} \cdot \mathcal{B}_{\text{vis}}(B_c^{(*)+}(2S) \to B_c^+\pi^+\pi^-)$



(e) $\Delta M = 0$ (f) $\Delta M = 35\,\text{MeV}$

$$\Delta M \equiv \left[M(B_c^{*+}) - M(B_c^+)\right] - \left[M(B_c^*(2S)^+) - M(B_c(2S)^+)\right]$$

- Compared to ATLAS [PRL 113 (2014) 12004]

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
ATLAS‡	$(0.22 \pm 0.08)/\varepsilon_7$	$(0.15 \pm 0.06)/\varepsilon_8$
LHCb	–	$< [0.04, 0.09]$ @ 95% CL

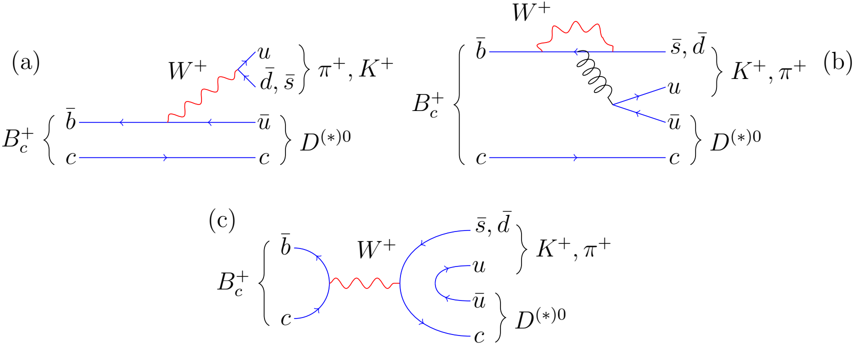
‡Estimated with B_c^+ / $B_c^{(*)}(2S)^+$ signal yields

$B_c^+ \to D^0 K^+$

[PRL 118 (2017) 111803]

- Several contributing processes, very interesting
  - (a) suppressed tree-level $b \to u$ transitions
  - (b) $b \to s$ loop-mediated (penguin) decays
  - (c) $\bar{b}c \to W^+ \to \bar{q}q$ annihilation

  Branching fraction may be enhanced by penguin and weak annihilation amplitudes

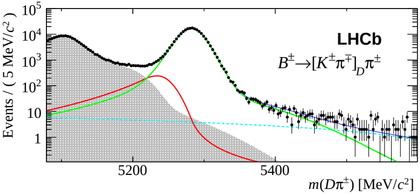


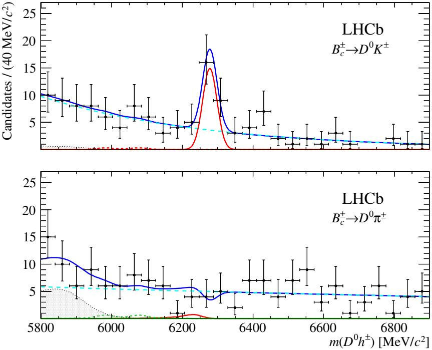
The meson appearing before the comma denotes the favoured decay.

$B_c^+ \to D^0 K^+$, results

[PRL 118 (2017) 111803]

- Using Run-I data, MVA-based selection
- $B_c^+ \to D^0 K^+$, observed with 5.1σ, including both $D^0 \to K^- \pi^+$, and $D^0 \to K^- 3\pi$. No $B_c^+ \to D^0 \pi^+$? $B_c^+ \to D^0 K^+$ predominantly through weak annihilation and penguin amplitudes
- Normalized to $B^+ \to D^0 \pi^+$,
  $\frac{f_c}{f_u} \cdot \mathcal{B}(B_c^+ \to D^0 K^+) = (9.3^{+2.8}_{-2.5} \pm 0.6) \times 10^{-7}$



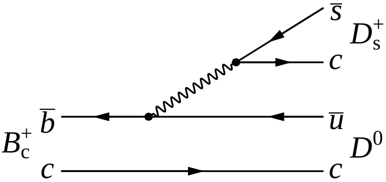


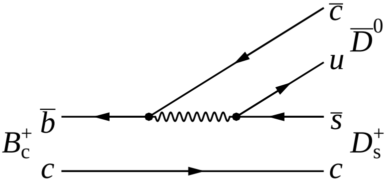
$B_c^+ \to D_{(s)}^{(*)+}\overline{D}^{(*)0}, D_{(s)}^{(*)+}D^{(*)0}$

[NPB 930 (2018) 563]

- Useful to measure CKM-angle γ, via the interference between $b \to u$ and $b \to c$ transitions.
- Compared to $B^+ \to DK^+$, $B_c^+ \to D_s^+ D$ has advantage ("less squeezed triangle")
  - Amplitude ratio $r(B_c^+) = \left| A(B_c^+ \to D^0 D_s^+)/A(B_c^+ \to \overline{D}^0 D_s^+) \right| \approx 1$, large CP asymmetry
  - Amplitude ratio $r(B) = \left| A(B^+ \to D^0 K^+)/A(B_c^+ \to \overline{D}^0 K^+) \right| \approx 0.1$, small CP asymmetry

  However very challenging as B_c^+ production cross-section is small

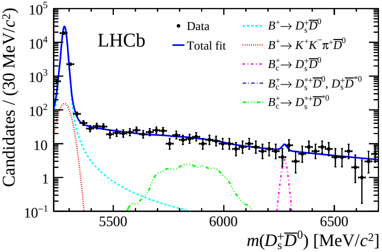


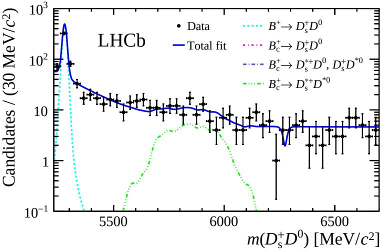


$B_c^+ \to D_{(s)}^{(*)+}\overline{D}^{(*)0}, D_{(s)}^{(*)+}D^{(*)0}$, results

[NPB 930 (2018) 563]

- Searched with Run-I data, no sign of signal yet.





- Setting upper limits @ 90% (95%) CL for 12 modes (2 shown, c.f. predicted $\mathcal{B} \sim 10^{-6}$)

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+\overline{D}^0)}{\mathcal{B}(B^+ \to D_s^+\overline{D}^0)} = (\quad 3.0 \pm 3.7) \times 10^{-4}\ [< 0.9\,(1.1) \times 10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ D^0)}{\mathcal{B}(B^+ \to D_s^+\overline{D}^0)} = (-3.8 \pm 2.6) \times 10^{-4}\ [< 3.7\,(4.7) \times 10^{-4}]$$

Summary

- LHCb has made big progress on B_c^+ studies with Run-I data
  - B_c^+ mass
  - B_c^+ lifetime
  - B_c^+ production
  - Many new B_c^+ decay modes: $B_c^+ \to B_s^0 \pi^+$, $B_c^+ \to D^0 K^+$
  - Search for $B_c^{(*)}(2S)^+$
- More studies on the B_c^+ meson will be done with more data, stay tuned